AD-761 190

THE ACCURACY OF ORBIT PREDICTION OF NON-COOPERATIVE EARTH SATELLITES

R. L. Duncombe

Center for Naval Analyses
Arlington, Virginia

13 June 1962

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

[redacted] DOWNGRADED TO
UNCLASSIFIED

9

UNCLASSIFIED

1

AD 761190

DDC

This is an interim report of continuing research. It does not necessarily represent the opinion of NAVWAG or the U. S. Navy. It may be modified or withdrawn at any time.

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151

NOTICE

THIS DOCUMENT HAS BEEN APPROVED FOR PUBLIC RELEASE

Interim Research Memorandum

NAVAL WARFARE ANALYSIS GROUP

WASHINGTON 25, D. C.

DOWNGRADED TO
UNCLASSIFIED

14

OFFICE OF THE CHIEF OF NAVAL OPERATIONS
LONG RANGE OBJECTIVES GROUP . . . OP-93

[redacted]

[redacted] DOWNGRADED TO UNCLASSIFIED

13 June 1962

Copy

NAVWAG INTERIM RESEARCH MEMORANDUM

Naval Warfare Analysis Group

THE ACCURACY OF ORBIT PREDICTION OF NON-COOPERATIVE EARTH SATELLITES (U)

By R. L. Duncombe

NIRM-8

This is an interim report of continuing research. It does not necessarily represent the opinion of NAVWAG or the U.S. Navy. It may be modified or withdrawn at any time.

DOWN[redacted]TERVALS;
D[redacted]YE[redacted]
[redacted]

[redacted]

FOREWORD

This paper, The Accuracy of Orbit Prediction of Non-Cooperative Earth Satellites, by R. L. Duncombe of the U. S. Naval Observatory, is one of a group of papers prepared as a result of a meeting of OEG consultants and other experts held on 18 January 1962 to assist NAVWAG in its study of certain aspects of the threat of hostile spacecraft to naval operations.

A resumé of the discussions at the meeting has already been published:

> Summary Report of the OEG Consultants Conference on the Threat of Hostile Spacecraft to Naval Operations Secret

and additional papers will be published shortly dealing with certain sensors in military satellites and with the accuracy of prediction of the orbits of active and passive satellites. No attempt has been made to reconcile the contents of the group of papers as a whole.

This document does not necessarily represent the opinion of OEG, NAVWAG, or the U. S. Navy.

~~CONFIDENTIAL~~ DOWNGRADED TO UNCLASSIFIED

ABSTRACT

Two systems for tracking passive (non-cooperating) satellites are considered: the Navy Space Surveillance System (NavSpaSur) and the "Millstone" active radar. Accuracy estimates are presented for both. Future improvements to both systems and combinations of them are also considered. The effect of large solar flares on prediction accuracy is estimated.

~~CONFIDENTIAL~~

DOWNGRADED TO UNCLASSIFIED

CONFIDENTIAL

THE ACCURACY OF ORBIT PREDICTION OF NON-COOPERATIVE EARTH SATELLITES (U)

At the present time the principal monitor of non-cooperative earth satellites is the U S Naval Space Surveillance System, (reference (a)) an electronic sensor spanning the southern United States. This system comprises several CW transmitters and interferometric receivers, and a central observation analysis and orbit prediction facility The system is able to monitor earth satellites having an orbital inclination of approximately 32° or greater The principal drawback of the system is that it is statically oriented with respect to the surface of the earth and hence must depend on the rotation of the earth to carry it to the orbital plane For the same reason its view is constrained to two regions of orbital longitude which change only because of the secular variations of the node and perigee. This restriction places definite limitations on the "one pass" capability of the system.

Of the other present methods of monitoring non-cooperative earth satellites probably the Millstone-type tracking radars are the most effective These steerable radars are capable of observing satellites over an extended arc of orbital longitude, thus providing better "one pass" capability than the NavSpaSur system. The principal restriction with this radar however is the effective area of search, which is so limited as to make the cost of complete sky monitoring by such equipment prohibitive.

The accuracy of orbit prediction is limited by several factors: a) errors of observation (including instrumental errors, refraction error, timing error, station errors, poor distribution in orbital longitude, etc); and b) inadequacies of theory arising from inability to anticipate variations in the atmospheric drag perturbation, inaccuracies of, or neglect of, terms in the disturbing potential, and uncertainties in the adopted astronomical and geodetic constants

Probably the largest body of observational data (although not the most accurate due to instrumental limitations) is that collected by the NavSpaSur system. Approximately 140 satellites are currently being observed representing a cross section of all objects launched to date. At present the elevation angles of the NavSpaSur system are recorded in analog form and can be resolved to only 1/20 of a degree, equivalent to a triangulation accuracy of 1 2 miles at a height of 1000 miles Because of this limitation in observational accuracy the orbit predictions

CONFIDENTIAL

are based on a restricted theory which incorporates only the secular perturbations and in some cases the larger periodic perturbations plus terms in the mean motion factored by the time and the time squared to represent the mean atmospheric drag perturbation. Within these restrictions the following statistics illustrate the average prediction accuracy obtainable with the NavSpaSur system for the present earth satellite population. For a sample of 108 satellites, (reference (b)), the error of prediction of a crossing of the NavSpaSur "fence" one week after the last observation included in the orbit correction is shown in Table I:

TABLE I

Pred. Error	No. of Satellites	Sum	Per Cent
0^s	20	20	19
1^s	33	53	49
2^s	23	76	70
3^s	9	85	79
4^s	3	88	81
5^s	4	92	85
$6\text{-}10^s$	8	100	93
$11\text{-}30^s$	6	106	98
30^s	2	108	

At the average height of this sample (350 miles) an error of one second is equivalent to slightly less than 5 miles displacement in orbit. The NavSpaSur system therefore shows an 85% capability to represent the positions of satellites in orbit one week in advance within 25 miles. Due to the low average height of the sample and the fact that many of the objects (such as burned out rocket casings, nose cone shields, etc.) have a high drag cross-section to mass ratio, the principal reason for this prediction error seems to be the inability to represent the atmospheric drag perturbation, especially in the last stages of orbital decay.

The uncertainty of predictions based on observations limited in orbital longitude is illustrated by the graphs in Figure 1, where predictions based on NavSpaSur observations only are compared with NASA observations well distributed in orbital longitude, (reference (b)). In both cases, however, about 90% of the observed lines of sight agree with the predictions within three tenths of a degree.

DOWNGRADED TO UNCLASSIFIED

CONFIDENTIAL

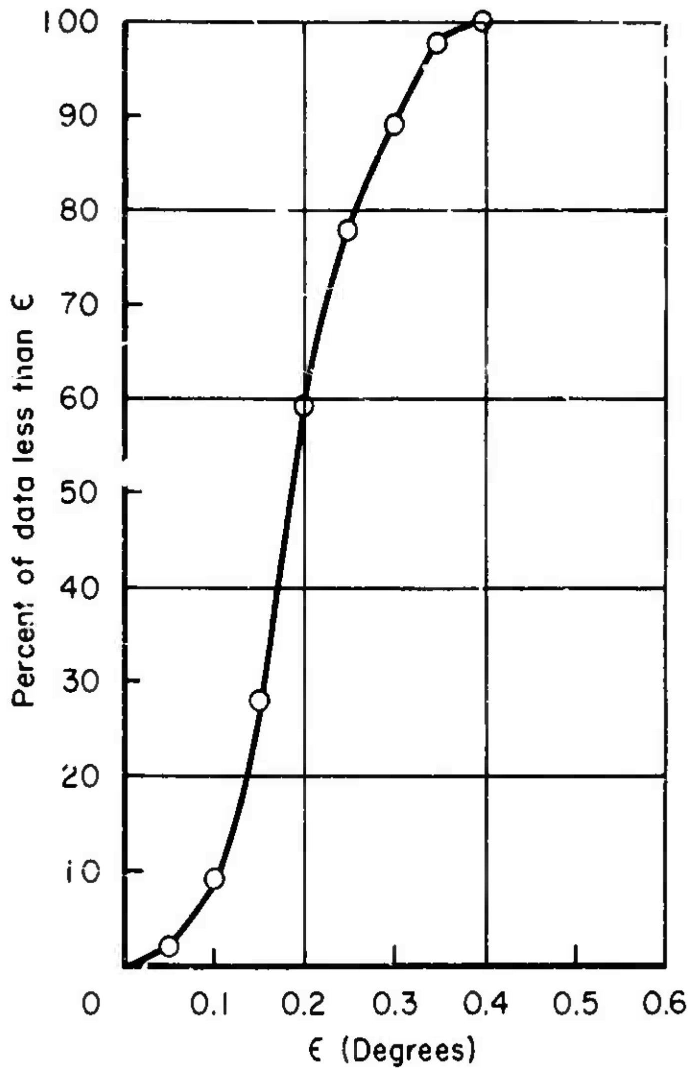

FIG. 1: DISTRIBUTION OF ANGULAR DIFFERENCE ϵ BETWEEN OBSERVED LINES OF SIGHT FROM SAO STATIONS AND PREDICTED LINES OF SIGHT FROM NAVSPASUR ELEMENTS FOR 1960 IOTA 2

CONFIDENTIAL

Another body of observational orbit data now being analysed is that from the NASA Mercury Project. Observations are made with FPS 16 and Verlort-type radars of a transponder mounted aboard the Mercury capsule. An analysis of the quality of the MA-5 real-time orbit determination by the Mercury Project tracking and computing complex by Schiesser, (reference (c)), indicates the following:

"a. The uncertainty in position appears to grow linearly with time for the limited period covered by MA-5 data.

"b. The FPS 16 is roughly twice as good as the Verlort-type radar for orbit determinations based on data from a single radar.

"c. There is a useful correlation between the precision of single radar orbit determinations and the maximum elevation of the vehicle with respect to the radar, which can be used to assess precision as a function of tracking conditions.

"d. Single radar orbit determinations based on data obtained to a maximum elevation much below ten degrees is nearly useless for accurately predicting the future position of a vehicle.

"e. Increasing the number of participating radars beyond any given number will not always result in greatly improved precision because of the influence of other important factors. For MA-5 the greatest improvement in precision occurred when the number of participating radars was increased from two to three."

He concludes that "when predicting ahead using a set of orbital elements determined in real time, the position of a vehicle will be known to lie within a sphere of radius U. For predictions up to two orbits ahead, it has been determined that U may be approximately by the expression:

$$U = A + B.t$$

where t (minutes) is the elapsed time from the time of the data used in the computation of the set of orbital elements to the time of interest."

For predictions based on observations from one radar only the value of A is approximately 700 yards for the FPS 16 and about 1600 yards for the Verlort-type radar. For single station observations, tracking to a maximum elevation of fifty degrees, B is found to be nearly 65 yards per minute for an FPS 16 and about 130 yards per minute for a Verlort-type radar. This leads to radii of uncertainty of 3.7 miles and 7.6 miles respectively for predictions one orbit in advance of the observations made by the FPS 16 or Verlort-type radar. For predictions based on observations by three stations, the mean values of A and B are 650 yards and 15 yards per minute respectively, leading to a radius of uncertainty one orbit in advance of 1.2 miles.

These figures must be considered to be the maximum prediction precision attainable with FPS 16 radar for a non-cooperative satellite of similar size and orbit. It is likely, due to the increased uncertainty of observations made without the aid of a transponder, that the actual prediction accuracy will be degraded by one or two orders of magnitude.

An extensive correlation of changes in the geomagnetic planetary index, as a result of solar flares, with the atmospheric drag perturbation effect on seven different earth satellites has been made by Jacchia, (reference (d)). The resulting accelerations are illustrated in Figure 2, taken from that report. This illustrates that for a satellite of similar mass and drag cross-section to Vanguard 1, at a height of 400 miles, an orbit prediction fitted to observations in the period Nov. 12.5-13.5 and having a mean epoch of Nov. 13.0 would be found not to represent an observation at Nov. 14.5 by slightly over two-tenths of a mile from this cause alone. It should be noted that the time between onset of the flares, as indicated by the arrows in the time argument, and the change in $\frac{dP}{dt}$ or the geomagnetic planetary index, is variable and presently unpredictable.

The number of solar flares of similar intensity (equal to or greater than 2+) recorded since mid-1958 are shown in Table II. The mean sunspot cycle, with which the incidence of these flares is correlated is shown in Figure 3.

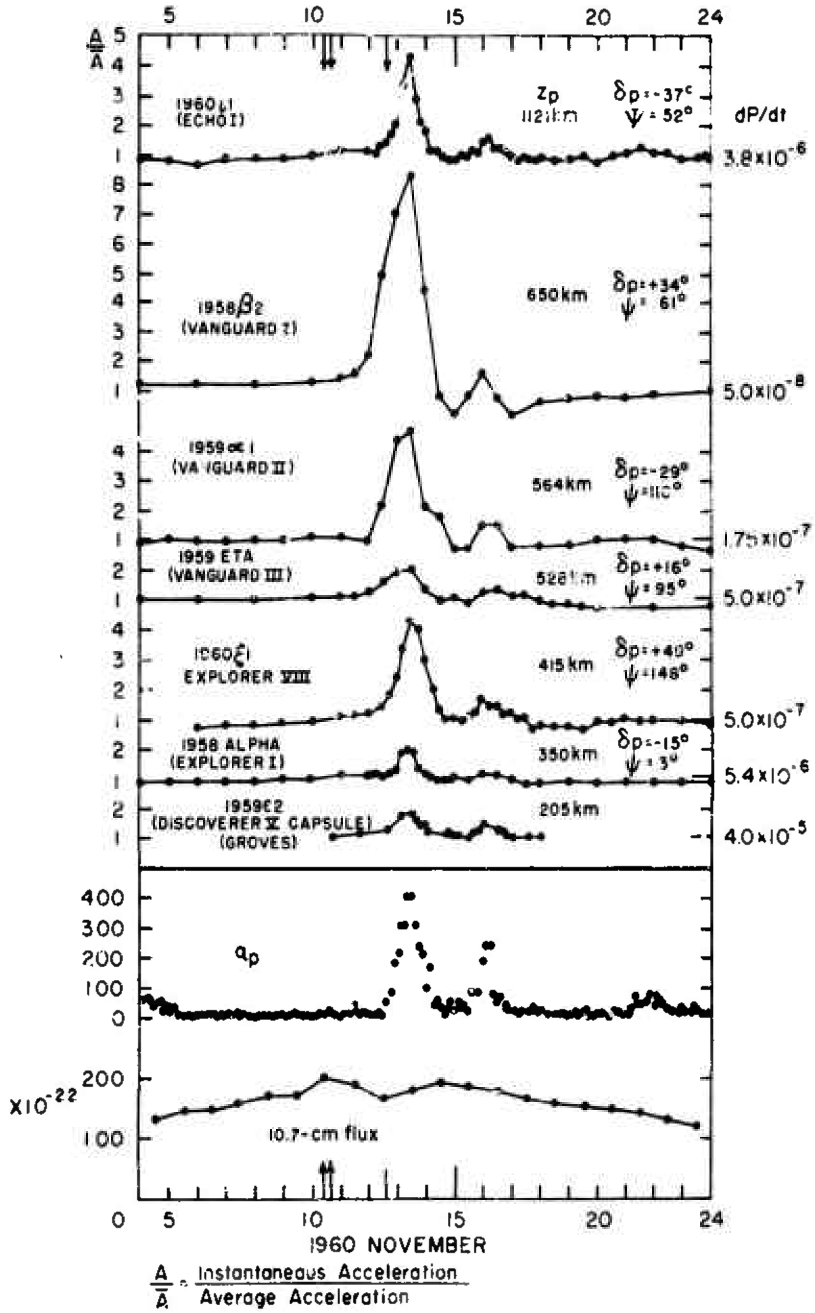

FIG. 2: ATMOSPHERIC DRAG OF SEVEN ARTIFICIAL SATELLITES DURING THE NOVEMBER 1960 EVENTS, COMPARED WITH THE GEOMAGNETIC PLANETARY INDEX α_p AND THE SOLAR FLUX AT 10.7 cm.

FOR DETAILED EXPLANATION, SEE TEXT.

DOWNGRADED TO UNCLASSIFIED

CONFIDENTIAL

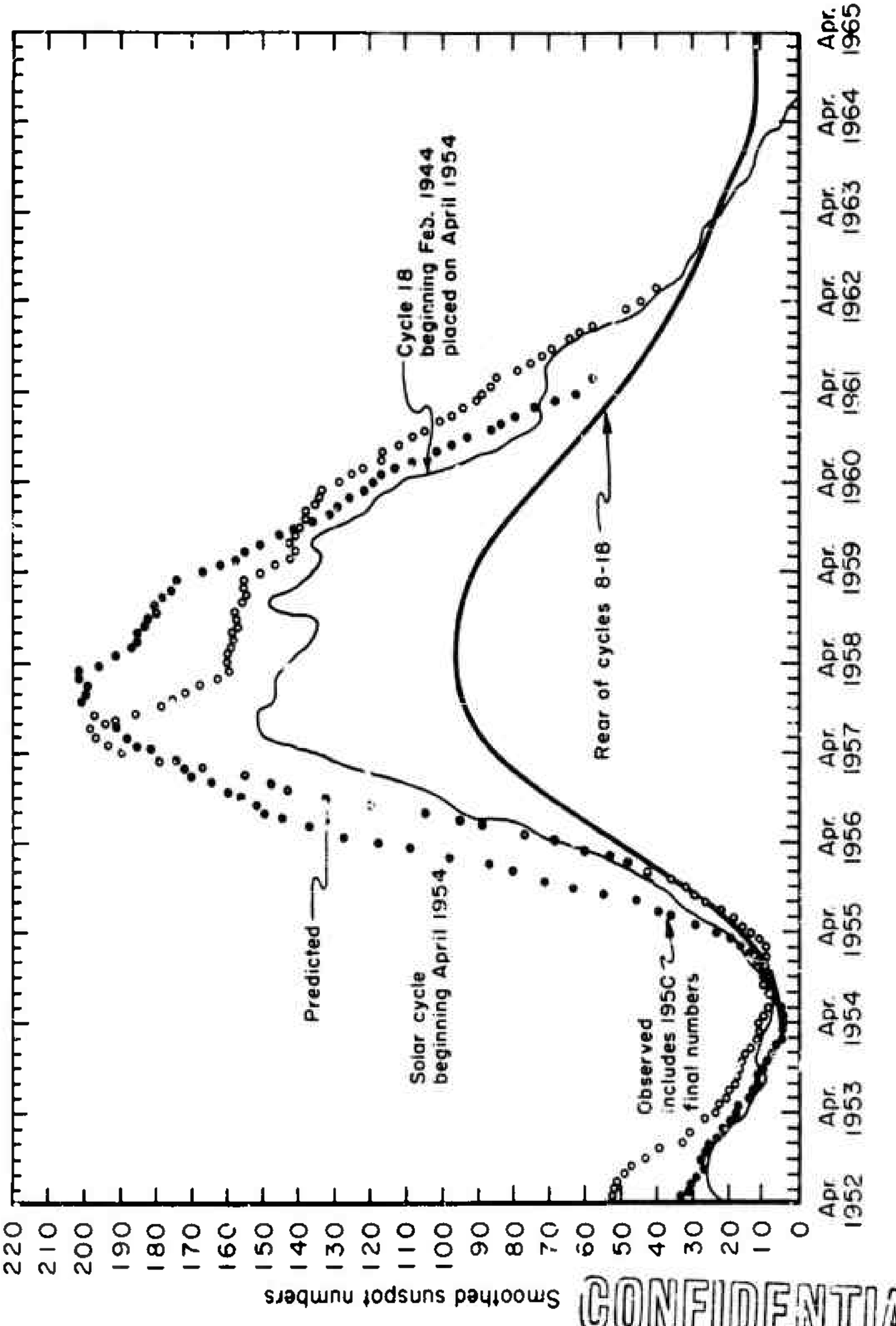

FIG. 3: PREDICTED AND OBSERVED SUNSPOT NUMBERS

CONFIDENTIAL

TABLE II

Solar Flares of Importance 2 +

	1958	1959	1960	1961
Jan.		14	2	-
Feb.		17	8	-
Mar.		14	6	1
Apr.		20	11	2
May		24	9	1
June		17	16	5
July	31	28	6	24
Aug.	29	15	13	2
Sept.	22	8	6	2
Oct.	20	-	9	-
Nov.	9	12	14	-
Dec.	15	4	1	1
Total	126	173	101	38

The foregoing evidence has been presented to indicate the accuracy with which the orbit of a non-cooperative satellite might be predicted, using first, NavSpaSur observations extending over several days and second, single pass observations of NASA Mercury Project collected from one or three stations.

Improvements in instrumentation and theory will undoubtedly occur in the next few years to greatly increase the capability of detecting and predicting the orbits of non-cooperative satellites. Kozai, (reference (e)), has summarized the most recent values of the constants associated with the zonal and tesseral harmonics in the potential of the earth as derived from the orbital variations of earth satellites. Further improvement in these and the geodetic constants may be expected from Project Anna. Probably the largest group of observations from which improved constants may be derived are those collected by Project Transit, although the numerous photographic observations of the Smithsonian Astrophysical Observatory tracking stations will be of value when precisely reduced. It may be noted that the next few years offer an excellent opportunity

DOWNGRADED TO
UNCLASSIFIED

CONFIDENTIAL

for collection of precise observations with a minimum of solar flare interference (see Figure 3). The most recently determined values of astronomical and geodetic constants have been reviewed by Kaula, (reference (f)) It is important to the future combination of observations and derivation of improved constants, that this or some other mutually agreeable set of constants be adopted for use by all earth satellite observing facilities.

Refinement of the presently used model of the earth's atmosphere must await the collection of earth satellite observations at higher altitudes and for various drag cross-section to mass ratios. Application of presently observed atmospheric drag effects to satellites outside the region of observation or of differing configuration may be subject to error because of presently unknown variations of atmospheric parameters. The atmospheric drag effect and unpredictable variations thereof will continue to be important to the accuracy of long, and short, range predictions of non-cooperative satellites; particularly those resulting from enemy action, which will be of greatest concern. It seems impossible to anticipate at what height to expect non-cooperative enemy satellites While higher altitudes would promote orbital stability for surveillance purposes, the trajectory of a missile from such a high satellite back to the surface of the earth would be long enough to allow detection and defensive action. On the other hand, for reasons of booster limitations or short mission life-time, non-cooperative enemy satellites might be placed in relatively low orbits. Under any circumstances, no precise information as to the mass or drag cross-section of enemy satellites will be available and hence prediction of their orbits will always be affected by the inaccuracy of our approximations to these parameters.

Current improvements in the power and instrumemtation of the NavSpaSur system will allow detection of targets of one square meter at a height of 2500 miles with a triangulation accuracy of .06 miles. Operation of this detection and spotting capability to give immediate alerts to steerable radar of similar accuracy in order to obtain observations over long arcs would seem to provide the best team for the detection and tracking of non-cooperative satellites.

Incorporating refined values of the astronomical and geodetic constants, improved values of the refraction and an extended model of the atmosphere with a complete gravitational theory, should produce real-time orbital predictions for non-cooperative earth satellites based on these observations having an accuracy one orbit in advance one order of magnitude better than that now attained with the Mercury tracking computing complex.

CONFIDENTIAL

References

(a) R. L. Easton and J. J. Fleming, "The Navy Space Surveillance System", Proceedings of the I R E, Vol. 48, No. 4, April 1960.

(b) Space Surveillance System - Technical Summary Report No. 5, U. S. Naval Research Laboratory, Washington, D. C., March 1, 1962.

(c) E. R. Schiesser, "Quality of the Real-time Orbit Determination by the Mercury Tracking-computing Complex", Memorandum for Chief, Flight Operations Division, NASA--Manned Spacecraft Center, Langley, Va., 29 March 1962.

(d) L. G. Jacchia, "The Atmospheric Drag of Artificial Satellites During the October 1960 and November 1960 Events", Smithsonian Institution, Astrophysical Observatory, Special Report No. 62, 26 May 1961.

(e) Y. Kozai, "Numerical Results from Orbits", presented at the Symposium on the Use of Artificial Satellites for Geodesy, April 26-28, 1962, U. S. Naval Observatory, Washington, D. C.

(f) W. M. Kaula, "Recommended Earth Gravitational and Geometrical Constants for Tracking and Orbit Computation", NASA Memorandum, 15 May 1961.